# Metamaterial labyrinth wall for very low and broad-band sound absorption

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May 30, 2020

**Abstract**

A metamaterial labyrinth wall for broad-band as well as very low-frequency sound absorption is presented, both with measurements walls in real-world cases, as well as in a Finite-Element Method (FEM) model. The measured cases are a glass wall in a recording studio and a wooden wall in a rehearsal space. The lowest damped frequencies measured for the glass wall is 44 Hz, while the lowest calculated frequency damped is at 5 Hz. Still the 5 Hz case cannot be measured with our equipment. The glass wall shows a flat damping spectrum from 20 Hz - 20 kHz with a mean sound attenuation of 38 dB. The wooden wall shows a frequency-dependent damping spectrum with a mean of 50 dB sound attenuation. Both walls are subject to sound deflection, especially the wooden wall, so the real attenuation is expected to be even higher. The presented geometry and size is found to be close to an optimum for sound attenuation with such labyrinths due to decoupling of labyrinth areas with larger labyrinths. Degenerated modes lead to a closer spectrum, where the glass wall shows 24 eigenmodes between 5 - 100 Hz. The wall is easy to built and light in weight, and might therefore be an alternative compared to other low-frequency damping methods, like room-in-room or bass traps.

## I Introduction

Absorption of walls used in room acoustics, like in concert halls, recording studio, rehearsal rooms, or in noise cancellation often fail to damp low frequencies. Room-in-room or bass trap solutions are capable to reach high low-frequency damping but are expensive to built. Still the need to low-frequency damping is there in all such cases. The present paper suggests a low-cost solution of a metamaterial wall, consisting of a labyrinth filled with air. Basically it can be built with all kinds of materials, as the cause of damping is the labyrinth structure. Still material with rough surfaces are preferable.

Traditional sound absorbing material is mainly based on bitumen-, liquid-, or nanotube materials [16]. They are based on viscoelasticity, where damping is strongest when the operation temperature of the material meets the glass-transition temperature. Complex frequency- and temperature-dependent damping curves appear with sandwich plates [17].

Using a center-finite-difference method is was shown that the appearance of frequency band-gaps in periodically stiffened plates is caused by the periodicity of the material and not mainly by viscoelastic effects[18]. The method used to estimate the damping behaviour is modal analysis which concentrates on the damped frequencies and not on the damping strength.

Metamaterials, like sonic crystals and related periodical structures, normally show band-gap damping appearing in the dispersion relation [5][6]. The band-gap nature of metamaterials is closely related to the band-gap damping known from viscoelastic effects[3].

Band-gap damping can also be realized with metamaterial membranes, using a massive ring on a regular membrane[15][8][14]. Band-gap damping due to acoustic cloaking [7] has already been applied to musical instruments[4].

Low-frequency absorption using metamaterials was shown using labyrinths [11], or using derivatives like spider webs[10], or accordon-like structures[9]. In all these cases the incoming wave is traveling through the plane of the structure which is quite large. The present application is also a labyrinth-like structure, still here the wave is entering perpendicular to the labyrinth plane.

Helmholtz resonators were also suggested for low-frequency sound absorption[12]. Although they slow excellent absorption these structures are very complex to build.

Alternative methods of reducing sound and noise are less successful, like green-wall absorption[1][2], reducing noise only around 10-20dB.

Two metamaterial walls built in real-world cases are discussed. A four-panel wall built of wood and glass was built in a recording studio, consisting of four single labyrinth panels coupled by wooden walls. A second case is a wall built of composite fiber plates. First the walls are discussed in more detail, while then presenting the Finite-Element Method (FEM) solutions for the walls. After discussing the measurement setups the measured and calculated results are compared.

## II Method

Two walls were built, one in a recording studio and one in a rehearsal room, formally being a garage. The recording studio wall can be moved sideways, but it is not feasible to take it out of the studio. The rehearsal room wall is movable, and was

Figure 1: Metamaterial wall in the recording studio as four labyrinth structures (four-panel). In the studio two such walls are present next to each other movable sideways.

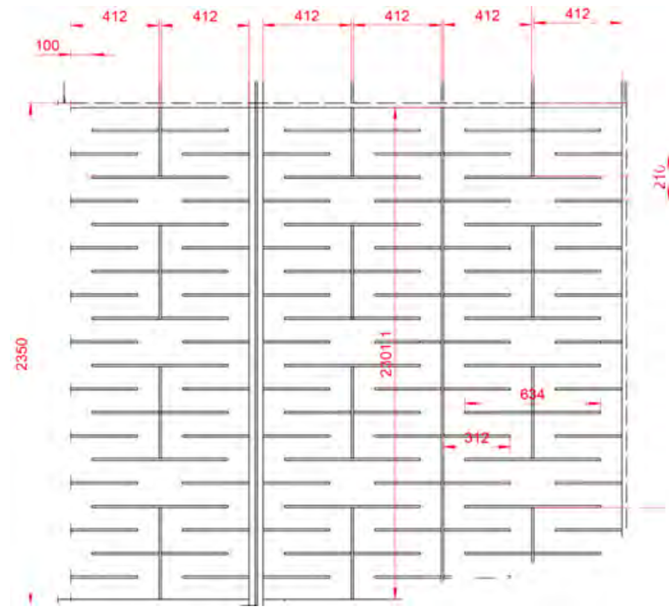


Figure 2: Labyrinth of the metamaterial wall in the rehearsal room. The left side is a door, while the right side is fixed. The left door wall was also measured in the anechoic chamber.

therefore measured in two setups, in the garage as a real-world case, and in the anechoic chamber at the Institute of Systematic Musicology.

The recording studio is of dimensions 10 m $\times$ 4.3 m, with a hight of 2.5 m = 107.5 $m^3$. In the middle of the longer wall of the studio a gap of 4.45 m $\times$ 2.17 m was present, as a reminder of a former corridor. This gap was closed with the metamaterial wall, consisting of two doors movable sidewards. Each door has a width of 2.29 m and a hight of 2.13 m, and consists of four metamaterial panels each, enclosed in a frame of a hollow wooden structure as shown in Fig. 1. The frame sides have a width of 13 cm, the top and bottom frames have a height of 18 cm. Each door consists of four labyrinth panels with the same labyrinth geometry each. They are covered with glass of a thickness of 10 mm. There are no further structures inside the labyrinth, so it is completely filled with air.

The metamaterial wall built in the garage is shown in Fig. 2.

has an overall width of 2.67 m with height 2.35 m. It consists of two parts, on the left the wall is built as a door of 0.93 m, on the right is a fixed wall of 1.74 m. Both sides have a depth of 12 cm, where the labyrinth air inclosed as a depth of 9.6 cm, so each wooden plate covering both sides of the labyrinth have a thickness of 1.3 cm. The wall is built at the open side of the garage, where the former wooden garage door is still in front, and can be closed to lock the room. The room has dimensions 4.90 m $\times$ 3.03 m $\times$ 2.45m = 36.38 m$^3$ and is built of concrete and has plain concrete walls. A small window of size 67 cm $\times$ 64 cm is placed at one side, where sound can freely exit. As the owner of the room wants this window to still be open we also left it open during the measurements to arrive at the real-world situation.

Using a Finite-Element Method (FEM), two cases of the metamaterial wall were calculated, a one panel and a four panel case. Additionally the sound transition attenuation of the built wall was measured with three microphone directivity characteristics, omnidirectional, cardioid, and shotgun.

## A Finite-Element eigenvalue calculation

A Finite-Element Method (FEM) was used to estimate the eigenfrequencies of the labyrinth wall. A two-dimensional solution was performed, as the third dimension is expected only to play a role for higher frequencies, where eigenmodes appear as standing waves with a wavelength half of the wall depth in the third dimension. As the wall depth is 8 cm we can expect the depth to play a role from about 4 kHz on. As we consider mainly low frequencies in the follow, a two-dimensional solution is expected to be sufficient.

A commercial software COMSOL was used to solve the differential equation for sound in air, with dependent variable $p(x, y)$ of the pressure field like

$$c^2 \left( \frac{\partial^2 p(x,y)}{\partial x^2} + \frac{\partial^2 p(x,y)}{\partial y^2} \right) = \omega^2 p(x,y) \ , \tag{1}$$

with speed of sound in air $c = 343 m/s$, and angular frequency $\omega = 2\pi\ f$ with frequency f.

One labyrinth panel of the recordings studio wall has a width of 1.012 m, a height of 0.885 m, and a depth of 10 cm. Wooden plates are used to built the labyrinth, as shown in Fig. 1, where the plates have a thickness of 7.5 mm and a depth of 8 cm. They separate the labyrinth channels. In the simulation they are taken as sound-proof walls with boundary condition of $\frac{\partial^2 p}{\partial \mathbf{x}} = 0$, where $\mathbf{x} = \{x, y\}$. For the one panel this boundary condition holds for all boundaries.

Then the width of the labyrinth channels in the lower and upper part of the panel have a width of $w_{Ch} = 0.50225m$ and a hight of $h_{Ch} = 0.104m$. Therefore the lowest frequency fitting in the channel width with half a wavelength is $f_w = 1366Hz$, and fitting in its height is $f_h = 6592Hz$.

Metamaterials have the property that they act on a subwavelength scale. Therefore the metamaterial behaviour should disappear above $f_w$, therefore above about 1.4 - 1.5 kHz, taking into account that the boundary conditions in the calculation are idle.

For the four-panel case four of the panels described above are combined as shown in Fig. 1. They are separated by a wooden plate of 7.5 mm thickness. This plate is modeled with a structural-mechanics equation like

$$\frac{E}{\varrho}\left(\frac{\partial^2 u(x,y)}{\partial x^2} + \nu \frac{\partial^2 v(x,y)}{\partial x(\partial y}\right) = \omega^2 u(x,y) \ ,$$
$$\frac{E}{\varrho}\left(\frac{\partial^2 v(x,y)}{\partial y^2} + \nu \frac{\partial^2 u(x,y)}{\partial y \partial x}\right) = \omega^2 v(x,y) \ ,$$

with u(x,y) and v(x,y) are the displacement fields of the domain in the x- and y- direction respectively, Young's modulus E = 13 GPa, and density $\varrho = 860 kg/m^3$ for spruce. Due to the length of the wooden plates being much longer than their width, only the Young's modulus of in-grain wood direction was used.

The coupling between air and wood was modeled using the Euler equation relating sound pressure p and displacements u and v like

$$\frac{1}{\varrho}\frac{\partial p(x,y)}{\partial x} = -\frac{\partial u(x,y)}{\partial t} \ ,$$
$$\frac{1}{\varrho}\frac{\partial p(x,y)}{\partial y} = -\frac{\partial v(x,y)}{\partial t} \ .$$

## B Measurement

A loudspeaker (GD TD 500 M for the recording studio, a Genelec 8050B for the rehearsal room, a ADAM Audio S3H for the anechoic chamber) was placed 10 cm in front of the wall. Two different sweeps were used, one from 20 Hz - 20 kHz and one from 20 Hz - 200 Hz, both logarithmic in frequency. Behind the wall, again with a distance of 10 cm, three microphones were placed right opposite to the middle of the loudspeakers bass membrane one after the other, recording both sweeps each.

Two basic setups were used, one with the wall between loudspeaker and microphones, and one without the wall between them. In the recording studio case the wall is a moving wall. Therefore the setup of loudspeaker and microphone could be kept, and only the wall was moved away, so the loudspeaker was radiating directly into the microphones without any obstacle between them.

With the rehearsal room the metamaterial wall has two sides, one is fixed, the other is a moving door. There the two cases, with and without wall between loudspeaker and microphone, was prepared such, that the loudspeaker was in the room and the microphones outside. When opening the door to measure the case without wall, the loudspeaker was moved away, the door opened and the loudspeaker placed at the exact same position as with the measurement with wall between loudspeaker and microphone.

With the anechoic chamber case the wall was placed to cover one corner of the anechoic space. The hight of the wall matched the hight of the chamber. The sides of the wall were placed at the two walls of the corner of the chamber respectively. Again loudspeaker and microphone had the same position in both cases, with and without wall between them. As the anechoic chamber has geometric elements at the walls to attenuate sound reflection, although the metamaterial wall was placed right at the chamber wall, air between the absorbing elements did not separate the space behind the wall from the front acoustically entirely, but allowed for sound deflection. One could also place the wall freely inside the chamber to obtain deflections. Still to come close to the real-world case of the garage with some deflection allowed, this measurement case was used.

So the two setups, the three microphones and the two sweeps, ended in a whole of twelve recordings for each of the three rooms.

In a pre-test in the recording studio the loudspeaker and the microphones were placed at a larger distance from the wall. Still the wall is a moving wall, and therefore has slits on the top, bottom, left and right side, where sound is transmitted through. Indeed with the setup of a closed wall, the recorded sound sounded strongly reverberated. It was assumed that this was caused by the sound to come strongly from the slits and other sideways rather than from the wall, as a sound transmission through the wall. Therefore the close setup of both, loudspeaker and microphone being placed 10 cm in front of the wall was chosen. Indeed the sound attenuation in this setup differed tremendously from the one where the loudspeaker and microphone were placed at larger distances from the wall.

The three microphones used were, an omnidirectional Behringer ECM 8000 (15 Hz - 20 kHz), an open cardioid Schoeps MK 22 (40 Hz - 28 kHz) and a Schoeps CMIT 5U shot-gun microphone (40 Hz - 20 kHz) with strong directional characteristics. This appeared necessary, as from the pretest it became clear that the slits around the wall were transmitting sound too. Therefore it was expected that the directional microphones are able to omit the sound radiated to a better extend than the onmidirectional or cardioid microphones do.

# III Results

## A Calculation

## B Modes of vibration

Fig. 3 shows the lowest eigenmode for one labyrinth with 44 Hz eigenfrequency. The mode shape has stronger amplitudes in the upper part of the wall compared to the lower one. This is arbitrary as the labyrinth is symmetric, and the mode could also appear turned around.

The idea of the wall is not only to damp one frequency, as would be the case with Helmholtz resonators, but higher eigenmodes exist. Fig. 4 shows such a higher eigenvalue at 139 Hz. The eigenmode is considerably more complex as expected.

Still the realized wall was shown in Fig. 1 is a set of four panels. Although their air channels are completely separated by wooden plates they still might show some coupling modes

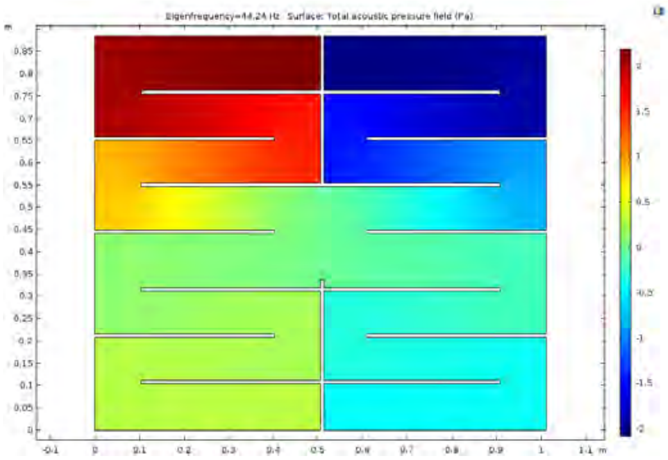

Figure 3: Lowest eigenfrequency at 44 Hz as a Finite-Element Method (FEM) solution for a two-dimensional wall with labyrinth structure (single panel).

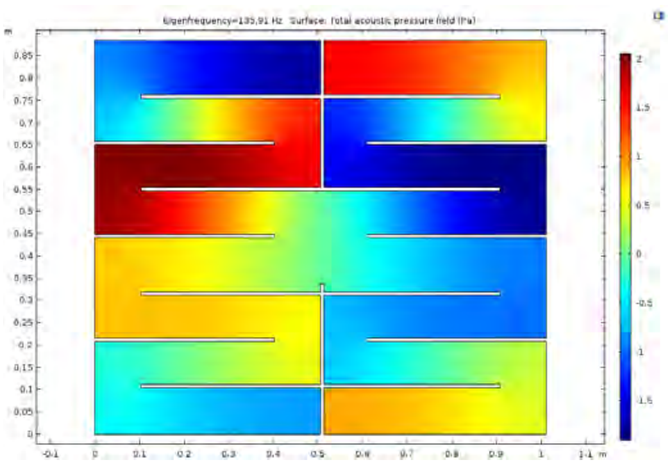

Figure 4: Eigenfrequency of 135 Hz of the single-panel wall.

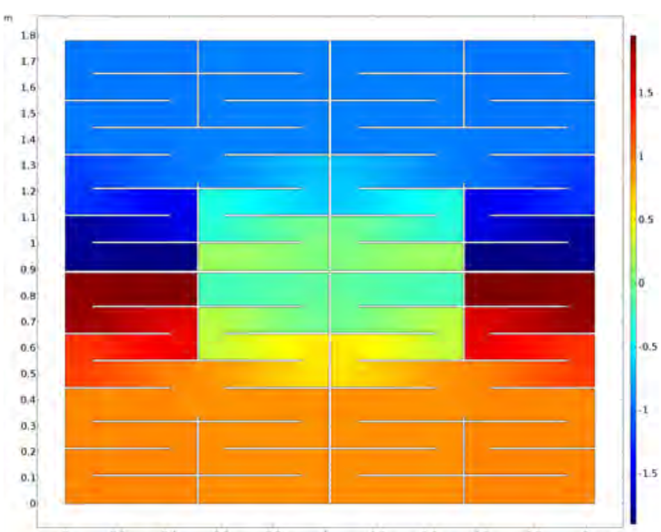

Figure 5: Lowest eigenmode of the four panel case at 5 Hz. A strong interaction between the four panels appear, as a common pressure at the center, as well as at all other surfaces between the panels.

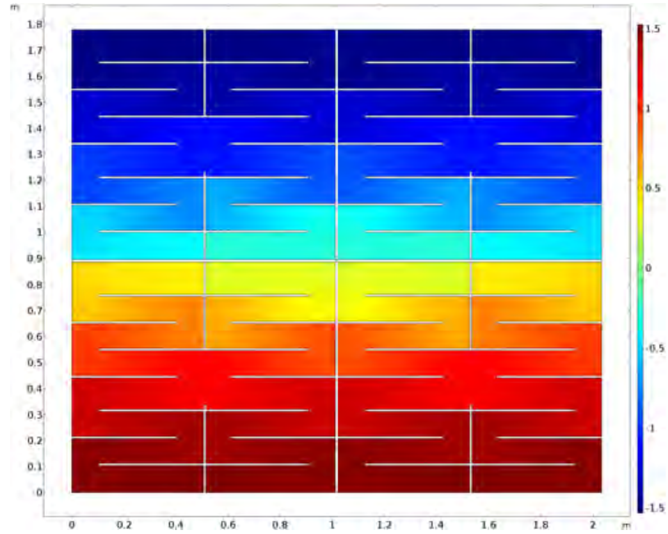

Figure 6: Eigenmode of the four panel case at 15 Hz as a dipole, again coupling all four panels.

between the panels. Then the lowest frequency might be even lower.

Fig. 5 shows the lowest eigenmode of the four panel case at 5 Hz, so below hearing threshold. Such a device might be interesting when attenuating infrasound e.g. from wind turbines. For the present case of a recording studio it seems to be of no use at first. Still having such a very low eigenmode means that in the low frequency range the density of the eigenmodes will be large enough to cover this domain much better, compared to the single-panel case with a lowest frequency of 44 Hz. The four panel system has 24 eigenmodes between 5 - 100 Hz, while the single panel has only 4 eigenfrequencies in this frequency range.

Overall the four-panel case has 866 eigenmodes between 5 - 2500 Hz, which is one eigenmode each 2.88 Hz as a mean. The one-panel case has 206 eigenmodes between 44 - 2500 Hz which is 12.6 Hz as a mean eigenfrequency distance. So the four-panel case has a eigenfrequency density which is large enough to cover practically the whole frequency range without considerable gaps.

The reduction of lowest eigenfrequency from 44 Hz with the single panel to 5 Hz with the four-panel setup is caused by a coupling between the four panels as shown in Fig. 5 and Fig. 6. Therefore the wooden walls are flexible enough to transmit low-frequency sounds, fusing the four panels into one. For higher modes this is not generally the case.

It might be expected that increasing the size of the labyrinth further, the lowest eigenfrequency could even drop. Therefore in the four-panel case, between the lower two labyrinths the lowest channels have been coupled by cutting out the wall between them over the hight of the lowest channel. Then the two lower labyrinths have one joined air space. But still the lowest eigenfrequency of this four-panel is at 5 Hz. Still now only 23 eigenmodes exist between 5 - 100 Hz, compared to 24 modes with the four-panel case of labyrinths completely separated by a wall. The lowest eigenmode at 5 Hz is the same as shown in Fig. 5. It seems that with even larger labyrinths the air space becomes too big and starts decoupling. Therefore the

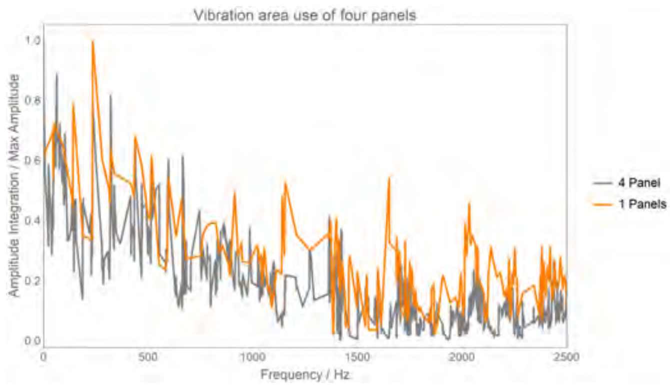


Figure 7: Frequency-dependent vibration areas as fraction of the integrated absolute pressure over the maximum absolute pressure for each eigenmode for the two cases of one panel and four panels. The one-panel case shows higher values throughout as expected, as it is the smaller geometry. The whole domain/ subarea threshold is reached at about 1.5 kHz as expected from theoretical considerations, still the plots decrease smoothly. Interestingly subarea vibrations already appear with very low frequencies.

suggested dimensions of the single labyrinth seems to be close to an optimum when seeking for the lowest possible frequency.

## C Vibrating area

The efficiency of sound attenuation of the wall depends on the distribution of the vibration in the wall for each eigenfrequency. Sound is mainly dissipated due to the movement of air at the walls, as sound in air has nearly no attenuation[13]. Therefore the larger the area in which vibration appears, the stronger the damping of the respective eigenmode. So comparing the one panel with the four panel setup we are interested to know if the four panels improve damping, despite its ability to better damp lower frequencies compared to the single-panel setup. Here we expect higher frequencies not to be distributed all over the whole setup, and only occupy a small subarea. The frequency threshold for the vibration to turn from a whole-domain vibration into subarea vibrations is of interest when deciding on the maximum panel size needed for certain applications.

Of course other features contribute strongly to the overall damping, like the wave speed, and so its frequency or the dissipation of the wave when traveling inside the wall. These are depending on material and below we compare the results for glass with the recording studio wall with wood for the rehearsal room.

To estimate the frequency threshold from whole-domain to subarea vibrations, the eigenmodes of the FEM solution were integrated with respect to absolute pressure over the air domains. These were divided by the maximum absolute pressure of the respective eigenmode, leading to an estimation of the vibration area for each eigenmode. The second normalization is necessary due to the random absolute pressure value calculated by the FEM solver. So high values of vibration area indicate that the vibration is present over most part of the domain, while low values indicate that only small areas of the domain experience the vibration.

Fig. 7 shows the vibration area for frequencies up to 2.5 kHz for the two cases of one and four panels. The one panel case has a mean vibrating area of 0.23, outperforming the four panel case with a mean of 0.17 a little bit over the whole frequency range. This is expected due to the larger area of the four-panel case. Still this does also hold for low frequencies. The threshold for whole-domain over subarea vibrations can be estimated to be around 1.5 kHz, still the transition is smooth, and at 1.5 kHz the curves are converged to quite small values.

It is interesting to see that subarea vibrations already exist in the very low frequency domain. Fig. 8 shows two eigenmodes of the four panel case at 34 Hz and 40 Hz, which form a degenerated pair. In both cases the vibration is not equally distributed over the geometry. Some areas vibrate strong, others barely. The optimum would be a coverage of the whole area to optimize sound absorption. Still as the modes are degenerated they form a pair within this frequency range, and add up together in sound absorption.

Fig. 9 shows two examples of higher modes at 1023 Hz and 2503 Hz. With 1023 Hz the wave number of this frequency is about the size of the labyrinth channels, with 2503 Hz its wave number is even higher. Here the metamaterial behaviour, acting on waves in the subwavelength domain, is barely or no longer fulfilled. Still this is not a real problem in terms of sound absorption, sound absorption generally is higher with higher frequencies, counterbalancing the reduced vibrating area. Indeed it is much more difficult to damp lower frequencies than higher ones in general. So the present device is able to damp both, very low and very high frequencies at the same time.

The reduced vibration area of the four-panel case does not mean that the four panels are less efficient in damping compared to the one-panel case. The modes of vibration shown in Fig. 7 are nearly all degenerated modes, very close in frequency, combining their absorption. Still the threshold of 1.5 kHz indicates the wall stops its metamaterial behaviour above 1.5 kHz, as then the wall is no longer acting on the incoming waves on the subwavelength scale.

## D Measurements

### 1 Recording Studio

Fig. 10 shows the attenuation through the wall for three microphones, an omnidirectional (black), a cardioid (gray) and a shotgun (light gray). When taking the highest peaks for the three cases, the lowest eigenfrequency is at 45 Hz, 44 Hz, 42 Hz respectively. Still neighoubring peaks exist with lower amplitudes. This is expected from the FEM calculation due to degenerated modes.

The on-panel wall has only frequencies at 44 Hz, 46 Hz, 48 Hz, 90 Hz up to 100 Hz. The four-panel case has 24 eigenfrequencies between 5 - 100 Hz, among them degenerated pairs around 55 Hz, 64 Hz, 74 Hz, and 90 Hz. Also there are eight modes from 5 - 44 Hz. The measured peaks up to 100 Hz differ between the microphones in amplitude, still there are more frequencies present than those of the one-panel case. Therefore we can assume that the additional frequencies are caused by the four-panel setup of the wall.

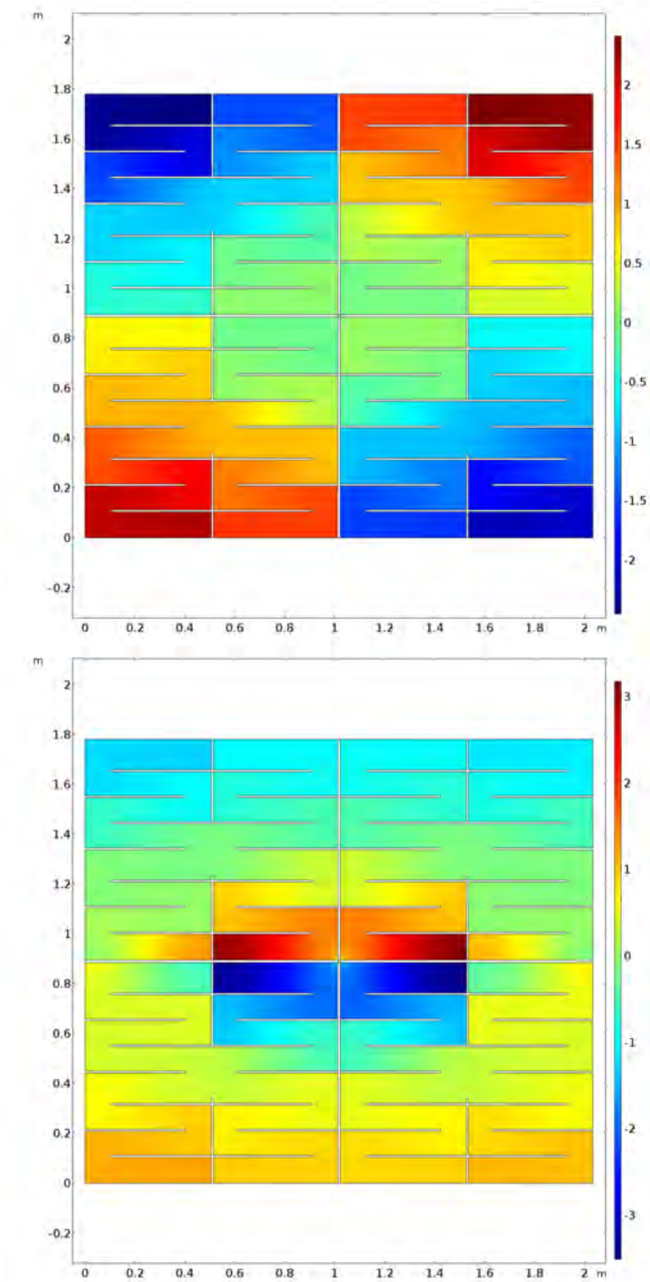


Figure 8: Degenerated eigenmodes at 34 Hz and 40 Hz of the four-panel case. The vibration of both are not equally distributed over the whole geometry, still as they are close in frequency they combine to a strong absorption in this frequency range.

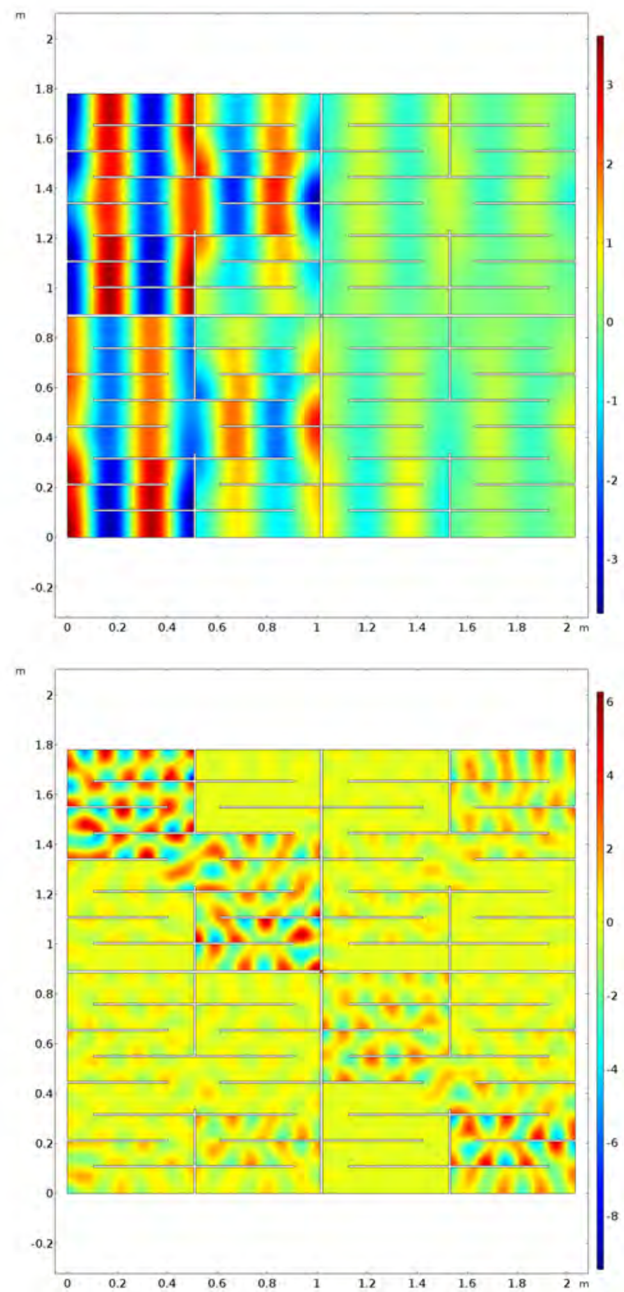


Figure 9: Eigenmodes of the four-panel case at 1023 Hz and 2503 Hz. Like with Fig. 8 the vibrations are not equally distributed over the wall.

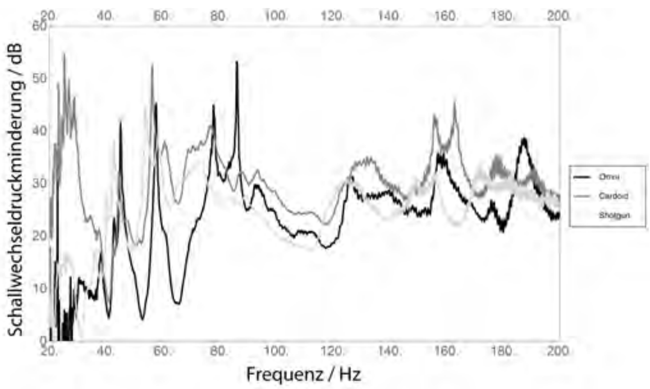


Figure 10: Pressure attenuation in dB comparing the case of a) the wall in between loudspeaker and microphone with the case b) of the wall not in between loudspeaker and microphone for 20 Hz - 200 Hz. Black: Omidirectional mic, Gray: cardioid mic, Light gray: Shotgun mic.

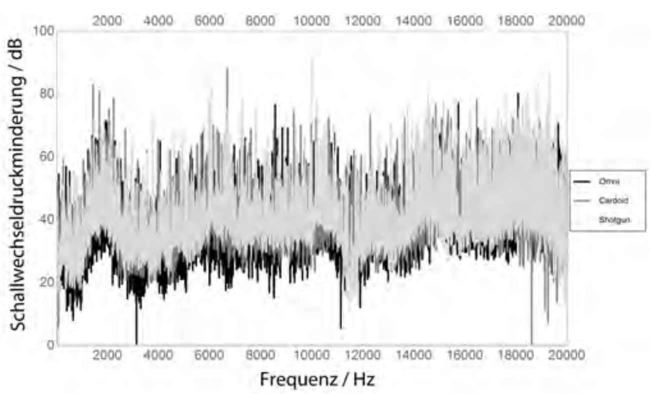


Figure 11: Pressure attenuation in dB as in Fig. 10 for 20 Hz - 20 kHz. The attenuation is nearly flat, with a positive regression slope of 2.5 dB (omni), 1.1 dB (cardioid), and 1.9 dB (shotgun) over 20 kHz.

The damping spectrum is nearly flat in all three cases, with a hill around 2 kHz. Over 20 Hz - 20 kHz the three microphones have a linear regression slope of 2.5 dB (omni), 1.1 dB (cardioid), and 1.9 dB (shotgun), which can be neglected. Therefore we can conclude that the wall is able to damp the whole spectrum of hearing about equally.

The mean sound attenuation for the three microphones are 33 dB (onmi), 36 dB (cardioid), and 38 dB (shotgun), pointing to deflection still appearing, although the loudspeaker and the microphone are close to the wall. Indeed the wall is made of glass mainly, which has a low sound absorption as a standalone material. As damping in the labyrinth can only happen at the boundaries, as discussed above, so at the glass or the wood between the glass plates, the smooth boundary of the glass is expected to result in lower damping as would be the case with more rough material. Still the wall was not built to damp out sound completely, and also due to aesthetic considerations glass was chosen.

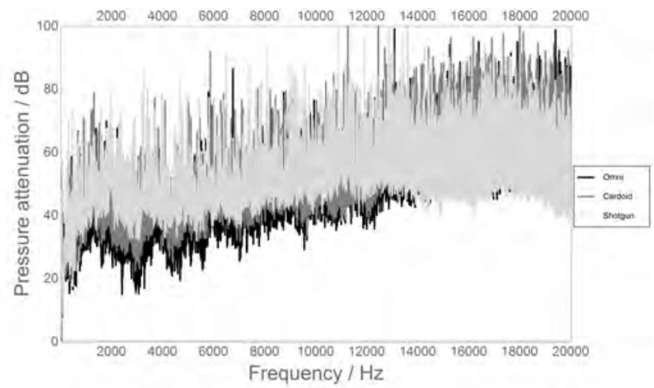


Figure 12: Measured pressure attenuation for the rehearsal room (garage) for 20 Hz - 20 kHz, again for all three microphone types. Compared to the recording studio case, a clear frequency-dependency appears, pointing to wave deflection around the wall.

### 2 Rehearsal room

The wall in the rehearsal room was measured at two locations, in the rehearsal room, as well as in an anechoic chamber. Fig. 12 shows the sound attenuation in dB for the rehearsal room situation, comparing the two cases, with and without wall between loudspeaker and microphone, again for three microphones. Contrary to the recording studio, a clear frequency-dependency of sound attenuation appears. This strongly points to sound deflection, where lower frequencies more easily travel around the wall. Therefore the lower attenuation at low frequencies compared to higher ones is most likely caused due to such deflection, and not due to a lower sound absorption efficiency for low frequencies.

The mean attenuation for the three microphone types as a mean over 20 Hz - 20 kHz is 45 dB (onmi), 50 dB (cardioid), and 50 dB (shotgun), again pointing to deflection. Also in Fig. 12 the onmi (black) curve has lower minima compared to cardioid and shotgun curves, strongly at lower frequencies and less nor no longer at higher frequencies, showing sound deflection influences.

This behaviour is also found for the anechoic chamber measurements of this wall shown in Fig. 13, only measured with an onmidirectional microphone. Mean sound attenuation is 35 dB in this case, where much more deflection happens due to the missing hard boundary walls in the anechoic chamber. Compared to the real-world case of 45 dB this obviously is caused by deflection.

## E Discussion

The metamaterial labyrinth structure shows high sound absorption over the whole frequency range. The measured lowest frequency of absorption here is 44 Hz, while the lowest calculated absorption frequency is at 5 Hz, which cannot be measured with our equipment. The glass wall at the recording studio has a nearly flat absorption all over the range of human hearing. The wooden wall shows a frequency-dependency, most likely caused by sound deflection, as confirmed in the anechoic chamber measurement of this wall.

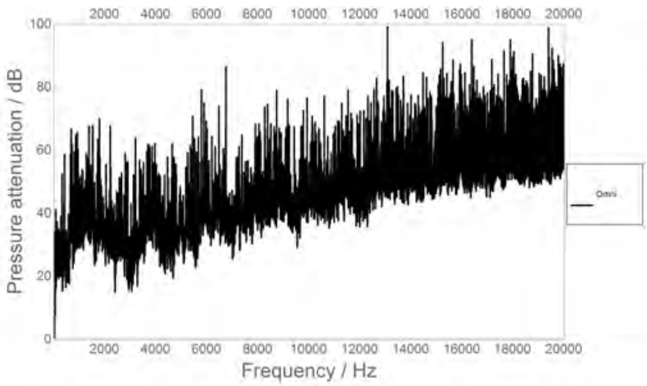


Figure 13: Anechoic room measurement of sound attenuation of one wall element of the rehearsal room shown in Fig. 12 with an onmidirectional microphone, allowing wave deflection. The frequency-dependent damping appears very similar to the real-world case.

Comparing the shotgun microphone measurements with least deflection impact, the metamaterial wall built with glass walls has a mean sound attenuation over 20 Hz - 20kHz of 38 dB, while the wall built of wood has a mean of 50 dB. This is expected, as damping mainly happens when the sound wave is moving inside the labyrinth at the labyrinth boundaries. Flat boundaries allow for a more smooth sound vibration, while a rough boundary is expected to cause turbulence, and therefore a much stronger damping. Additionally, when traveling through the material damping happens, again stronger in wood than in glass.

The metamaterial behaviour for the recording studio wall is only present for frequencies below about 1.5 kHz. This is consistent with the basic behaviour of metamaterials, which cause damping when the structure has dimensions in the sub-wavelength size of the damped wave. The labyrinth channel size thereby fits half a wavelength at about 1.5 kHz, which also coincides with the vibrating area of modeled eigenmodes converging at about 1.5 kHz.

Enlarging the labyrinth by combining two by coupling their air channels over one channel height does not lead to lower eigenmodes, but rather decrease the amount of eigenfrequencies up to 100 Hz. This is caused by a decoupling of larger labyrinth structures. Therefore the proposed metamaterial size and labyrinth structure seem to be close to an optimum when it comes to low-frequency damping.

The metamaterial wall might therefore be a structure able to damp very low frequencies within a comparable small geometry, light in weight and easy to built. It might contribute to sound attenuation in many cases. Still for low frequencies deflection around the wall need carefully to be taken into consideration, which decreases the efficiency, especially at low frequencies.

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